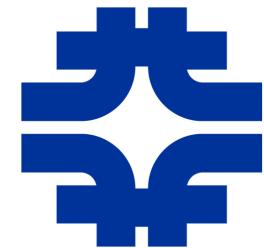


# Production of single top quark - results from the Tevatron and the LHC-

Chang-Seong Moon\*

on behalf of ATLAS, CDF, CMS and DØ collaborations  
Université Paris Diderot/CNRS & INFN-Sezione di Pisa



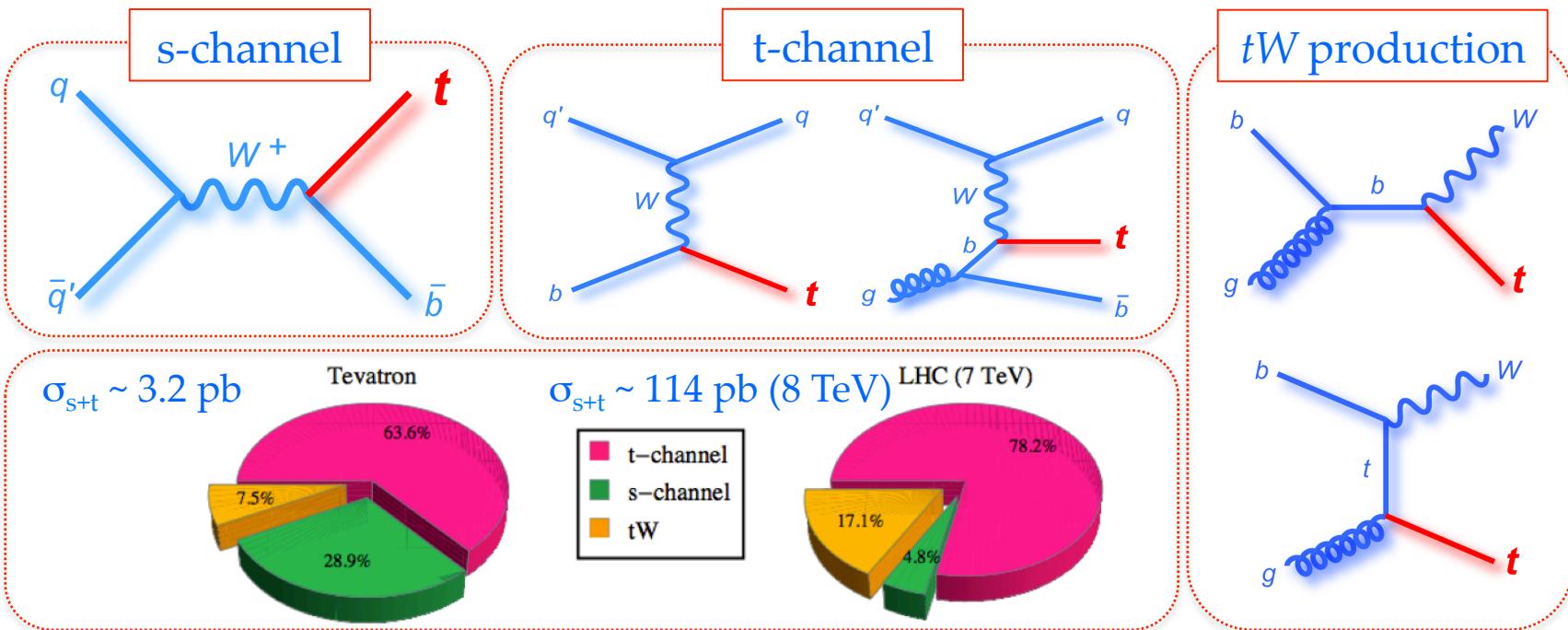
The 26th Rencontres de Blois  
Blois, 18-23 May 2014



\*Supported by the EU-MC-IIF project 302103, "TauKitForNewPhysics"

# Single Top Production

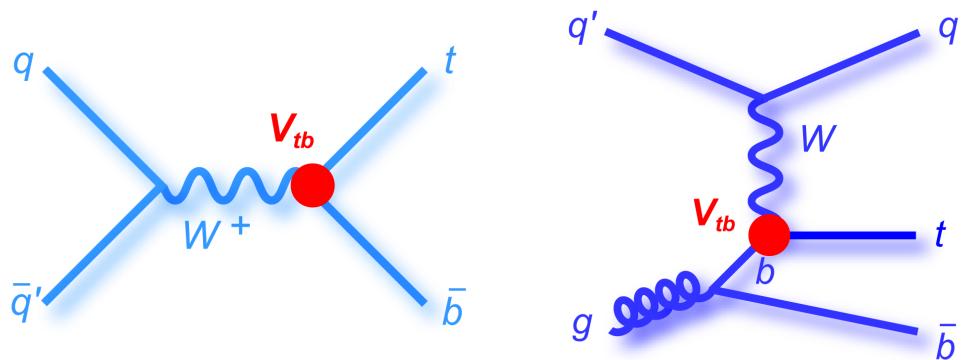
- ✓ Top quarks are produced singly in  $p\bar{p}$  or  $pp$  collisions via the electroweak interaction.
- ✓ First observed by the CDF and DØ experiments at the Tevatron.
- ✓ Three processes in the SM
  - t-channel, s-channel, and associated production of a top quark and a W boson.



- ✓ Challenging to overcome large background for extraction of the single top signal.
- ✓ Recently many new results have been reported from the Tevatron and LHC.

# Physics Motivation

- ✓ Test of the SM prediction
  - Direct measurement of the CKM matrix element  $|V_{tb}|$ .
  - t-channel single top production cross section provides a test of the b parton distribution function of the proton.



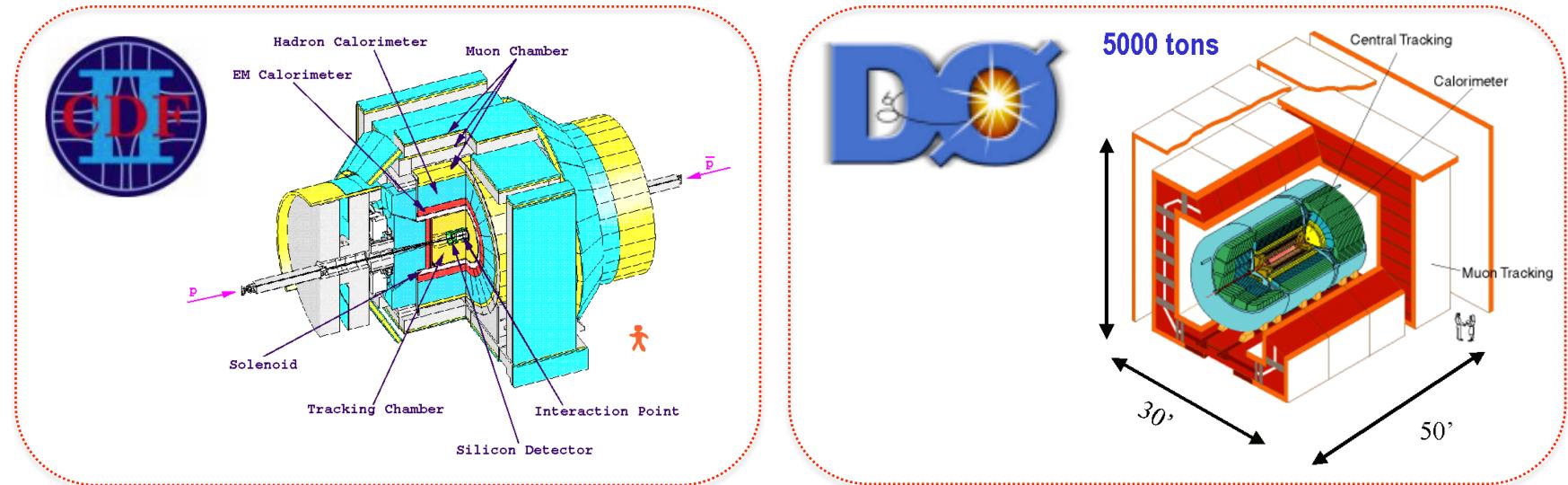
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- ✓ Sensitive to new physics process.
  - Existence of a fourth generation of fermions remains possible.
  - Flavor-changing  $Ztc$  coupling, (e.g. production of  $p\bar{p} \rightarrow t\bar{c}$ )
  - Additional charged gauge boson  $W'$
  - Charged Higgs production
- ✓ Important background to Higgs production.



# Single top at the Tevatron

- ✓  $p\bar{p}$  collision at  $\sqrt{s} = 1.96$  TeV
- ✓ CDF and DØ experiments
- ✓ Run II (2001–11) :  $\sim 12 \text{ fb}^{-1}$  delivered ( $\sim 10 \text{ fb}^{-1}$  recorded)
- ✓ The s and t channel processes are dominant. advantage in s-channel studies but negligible  $tW$  production.
  - $\sigma_s = 1.05 \pm 0.06 \text{ pb}$  (NLO+NNLL,  $m_{\text{top}} = 172.5 \text{ GeV}$ )
    - Kidonakis, PRD 81, 054028 (2010)
  - $\sigma_t = 2.12 \pm 0.16 \text{ pb}$  (NLO+NNLL,  $m_{\text{top}} = 172.5 \text{ GeV}$ )
    - Kidonakis, PRD 83, 091503 (2011)





# Single top in $lvb\bar{b}$ with $7.5 \text{ fb}^{-1}$

✓ s + t +  $tW$  combined cross section measurement

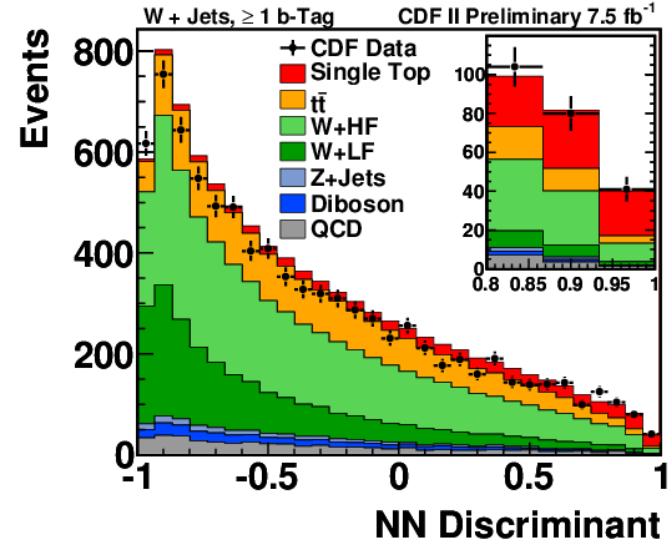
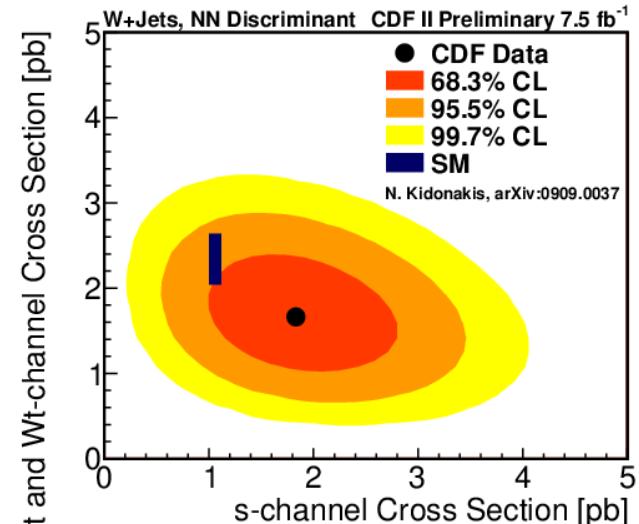
✓ Event Selection

- 1 high  $p_T$  electron or muon ( $P_T > 20 \text{ GeV}/c$ )
- Missing Transverse Energy(MET)  $> 25 \text{ GeV}/c^2$
- 2 or 3 jets ( $E_T > 20 \text{ GeV}/c^2$ )
- At least one b-tagging

✓ Result

- $\sigma = 3.04^{+0.57}_{-0.53} \text{ pb } (m_{\text{top}} = 172.5 \text{ GeV})$
- 2D fit for s-channel and t-channel
  - $\sigma_s = 1.81^{+0.63}_{-0.58} \text{ pb}, \sigma_t = 1.49^{+0.47}_{-0.42} \text{ pb}$
- $|V_{tb}| = 0.96 \pm 0.09(\text{stat. + syst.}) \pm 0.05(\text{theory})$
- 95% confidence level lower limit of  $|V_{tb}| > 0.78$

Processes	W + 2 jets, 1 tag	W + 3 jets, 1 tag	W + 2 jets, 2 tag	W + 3 jets, 2 tag
$t\bar{t}$	$474 \pm 49$	$1067 \pm 109$	$98 \pm 14$	$284 \pm 42$
WW	$148 \pm 21$	$48 \pm 7$	$1.1 \pm 0.3$	$1.2 \pm 0.3$
WZ	$53 \pm 6$	$14 \pm 2$	$8.8 \pm 1.3$	$2.4 \pm 0.4$
ZZ	$1.7 \pm 0.2$	$0.7 \pm 0.1$	$0.3 \pm 0.0$	$0.1 \pm 0.0$
Z+Jets	$118 \pm 15$	$46 \pm 6$	$4.8 \pm 0.7$	$2.7 \pm 0.4$
Wbb	$1452 \pm 437$	$434 \pm 131$	$183 \pm 56$	$65 \pm 20$
Wcc	$766 \pm 233$	$254 \pm 77$	$10 \pm 3$	$7 \pm 2$
Wcj	$583 \pm 177$	$128 \pm 39$	$7.8 \pm 2.4$	$3.5 \pm 1.1$
W+Mistags	$1459 \pm 148$	$433 \pm 47$	$7.4 \pm 1.5$	$5.4 \pm 1.1$
Non-W	$316 \pm 126$	$141 \pm 57$	$6.8 \pm 3.5$	$3.4 \pm 3.2$
t-channel	$193 \pm 25$	$84 \pm 11$	$6 \pm 1$	$15 \pm 2.4$
s-channel	$128 \pm 11$	$43 \pm 4$	$32 \pm 4$	$12 \pm 1.6$
Wt-channel	$16 \pm 4$	$26 \pm 7$	$0.7 \pm 0.2$	$2.3 \pm 0.6$
Total Prediction	$5707 \pm 877$	$2719 \pm 293$	$367 \pm 66$	$403 \pm 53$
Observed	$5533$	$2432$	$335$	$355$





# Single top in $E_T^{miss} b\bar{b}$ with 9.5 fb<sup>-1</sup>

✓ s + t combined cross section measurement

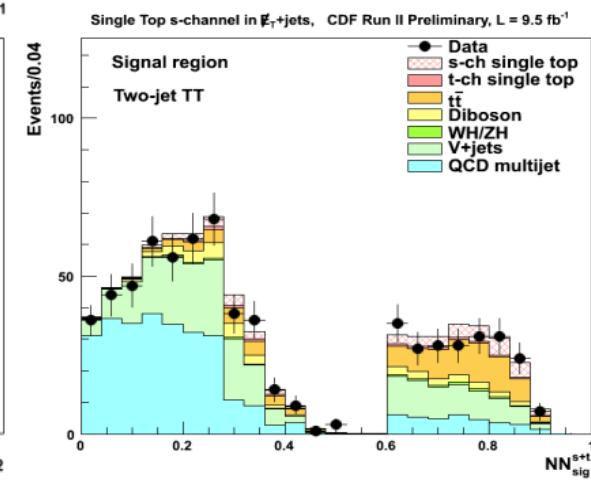
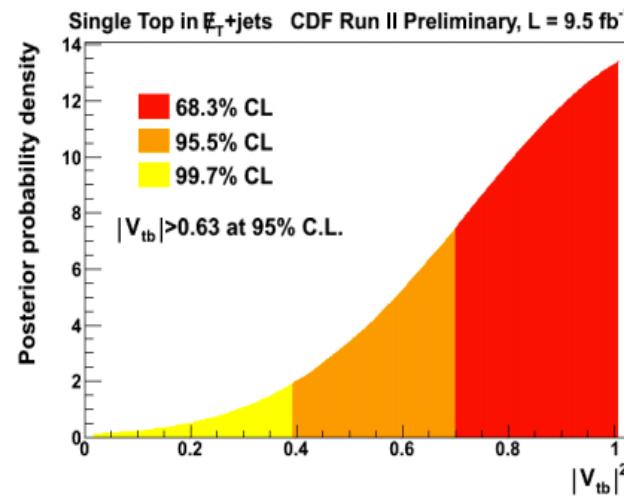
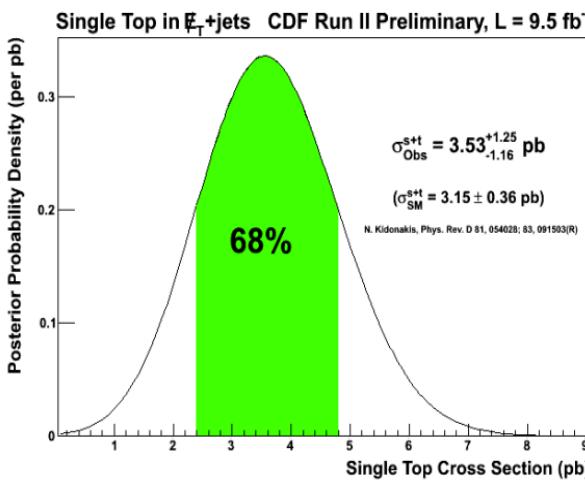
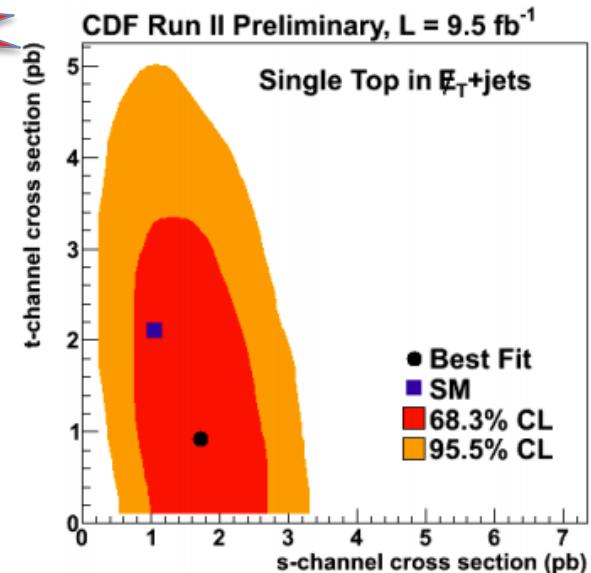
✓ Event Selection

- Reject events with isolated leptons
- MET > 50 GeV/c<sup>2</sup>
- 2 or 3 jets and one of the leading jets central ( $|\eta| < 1$ ).
- $\Delta R$  (leading jets) > 0.8
- At least one b-tagging

✓ Result

- $\sigma_{s+t} = 3.53^{+1.25}_{-1.16}$  pb ( $m_{top} = 172.5$  GeV)
  - SM prediction:  $3.15 \pm 0.36$  pb Kidonakis, Phys. Rev. D 74, 114012 (2006).
- $|V_{tb}| > 0.63$  at 95 % C.L.

New



# Single top in $lvbb\bar{b}$ with $9.7 \text{ fb}^{-1}$

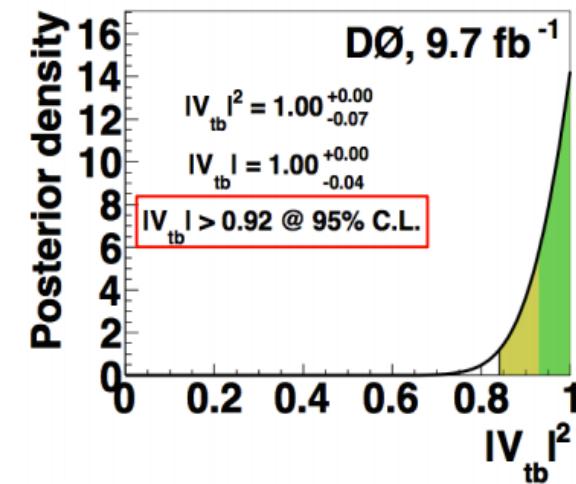
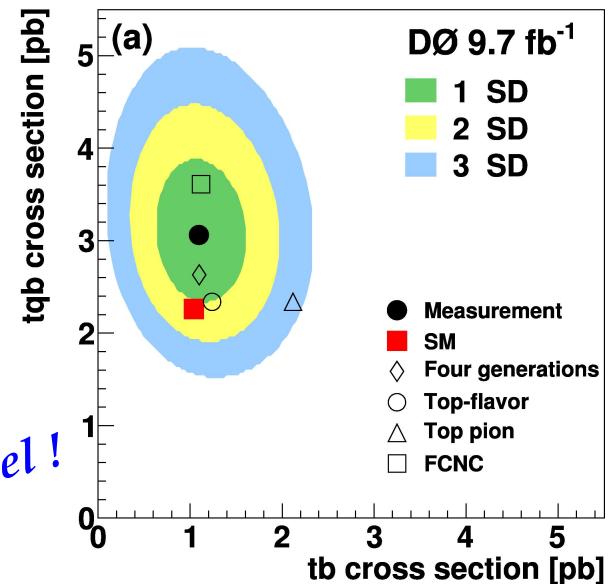
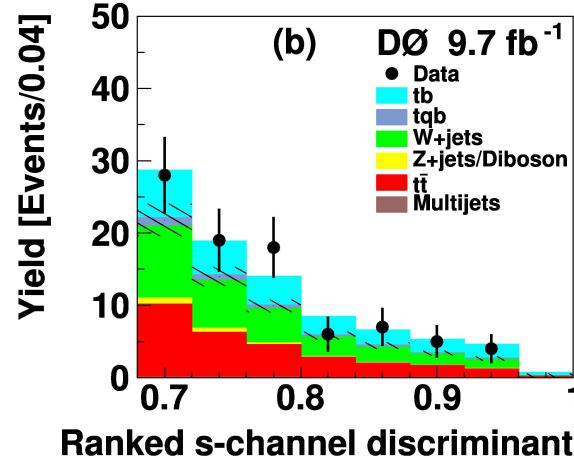
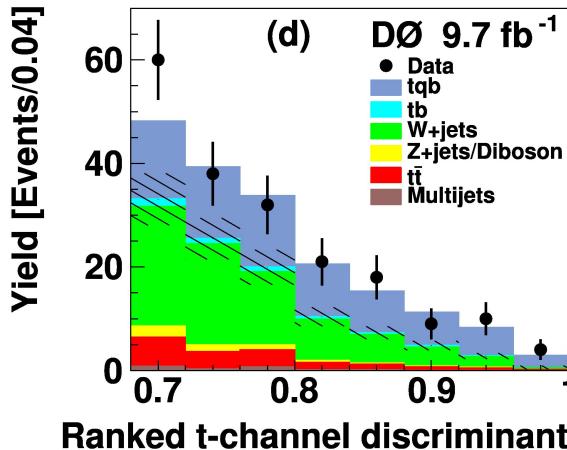
## ✓ Event Selection

- 1 high  $p_T$  electron or muon ( $P_T > 20 \text{ GeV}/c$ )
- MET  $> 20(2 \text{ jets})$  or  $25(3 \text{ jets}) \text{ GeV}/c^2$
- 2 or 3 jets ( $E_T > 20$  or  $25(\text{leading jet}) \text{ GeV}/c^2$ )
- At least one b-tagging

## ✓ Result

- $\sigma_{s+t} = 4.11^{+0.59}_{-0.55} \text{ pb}$  (SM prediction :  $3.34^{+0.53}_{-0.49} \text{ pb}$ )
- Simultaneous 2D measurements
  - $\sigma_s = 1.10^{+0.33}_{-0.31} \text{ pb}$  :  $3.7\sigma$  ( $3.7\sigma$  expected)
  - $\sigma_t = 3.07^{+0.53}_{-0.49} \text{ pb}$  :  $7.7\sigma$  ( $6.0\sigma$  expected)
- $0.92 < |V_{tb}| \leq 1$  at 95% C.L.

*First evidence of s-channel !*





# Evidence of s-channel at CDF

## ✓ $lv\bar{b}\bar{b}$ analysis

- $\sigma = 1.41^{+0.44}_{-0.42} \text{ pb } (m_{\text{top}} = 172.5 \text{ GeV})$
- Observed p-value :  **$3.8\sigma$  ( $2.9\sigma$  expected)**
- Accepted to publish in PRL at Apr. 21, 2014 (arXiv:1402.0484)

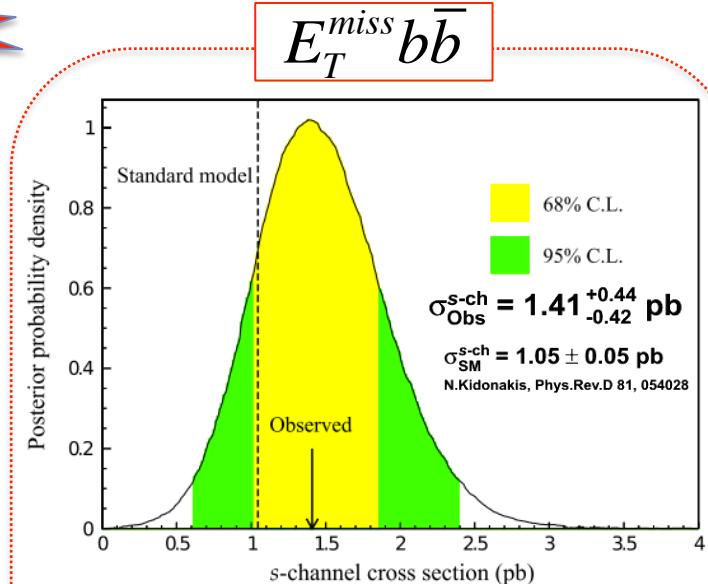
## ✓ $E_T^{\text{miss}} b\bar{b}$ analysis

- $\sigma = 1.12^{+0.61}_{-0.57} \text{ pb } (m_{\text{top}} = 172.5 \text{ GeV})$
- Observed p-value :  **$1.9\sigma$  ( $1.8\sigma$  expected)**
- Accepted to publish in PRL at May 1, 2014 (arXiv:1402.3756)

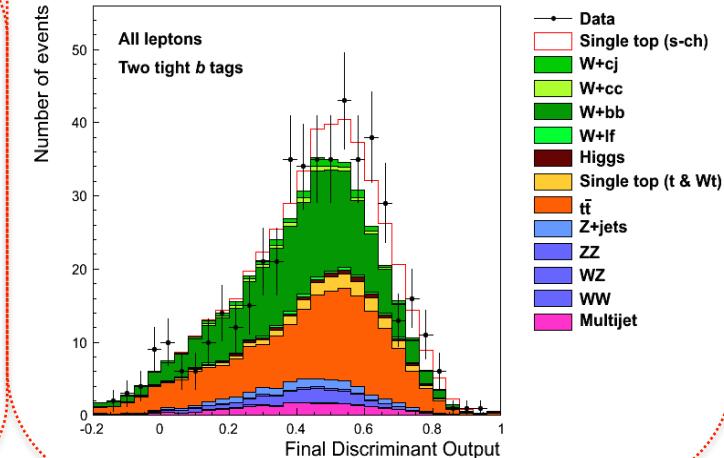
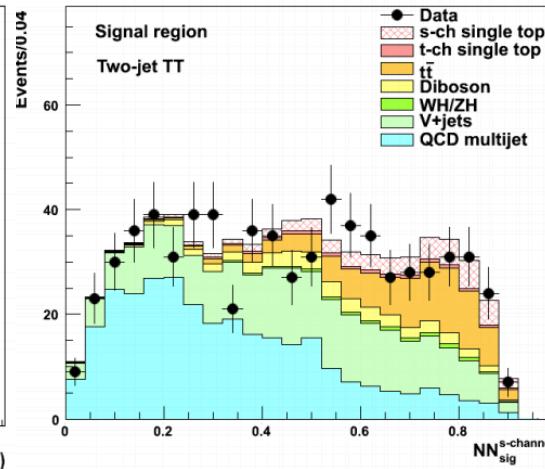
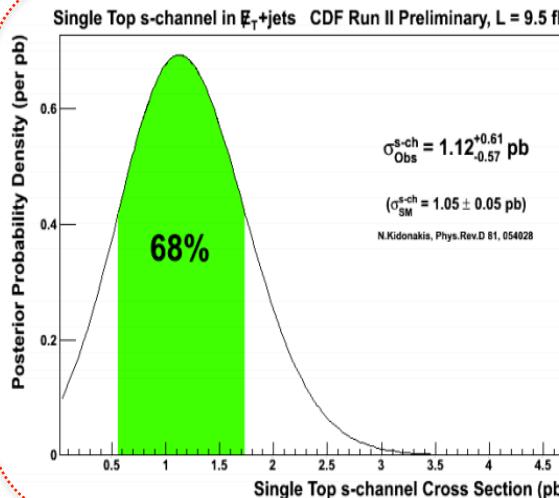
*Confirmed the evidence of s-channel !*

New

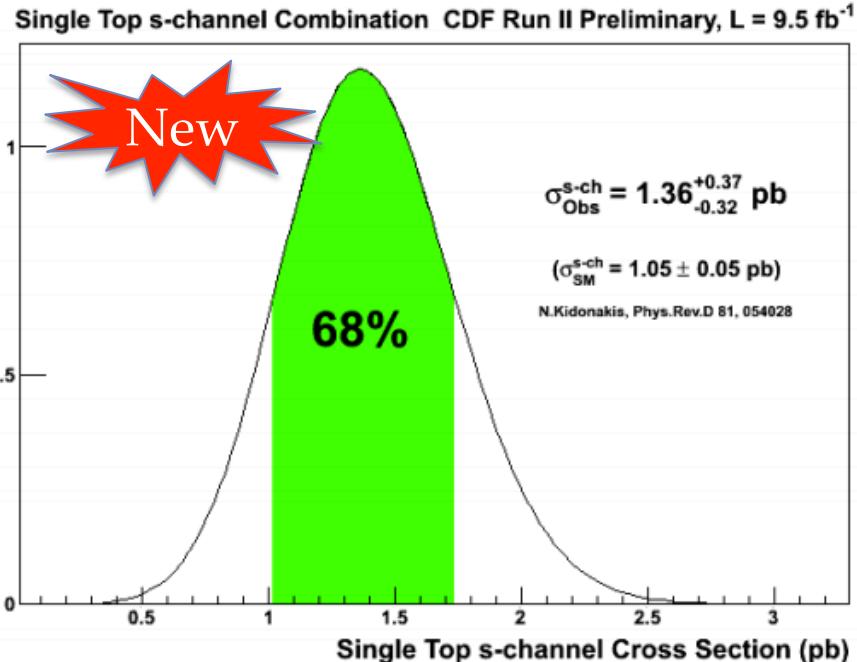
$E_T^{\text{miss}} b\bar{b}$



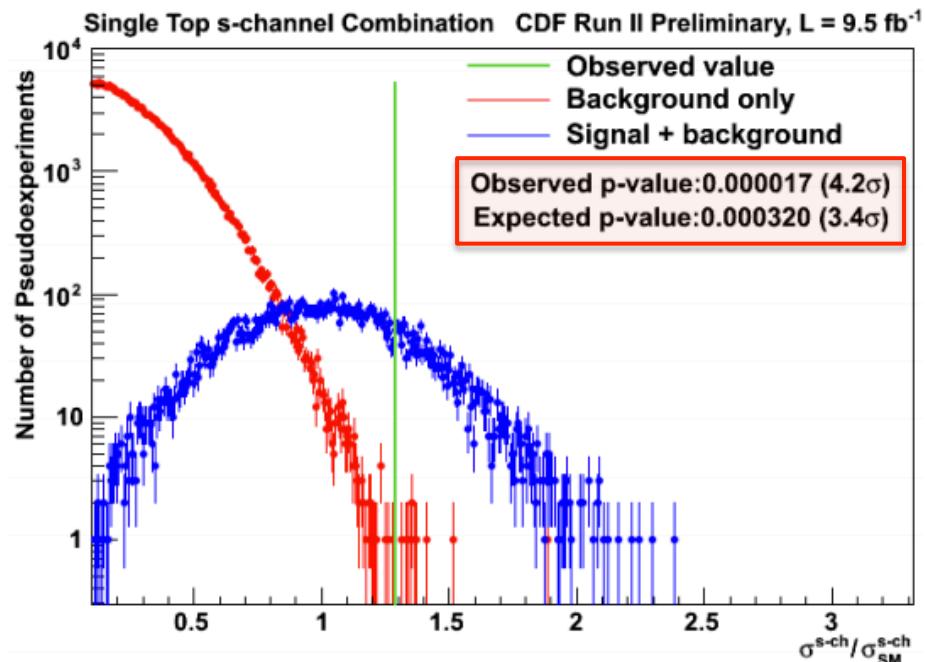
$lv\bar{b}\bar{b}$



# New CDF s-channel combination



$$\sigma_{\text{Obs}}^{\text{s-ch}} = 1.36^{+0.37}_{-0.32} \text{ pb}$$



$$(\sigma_{\text{SM}}^{\text{s-ch}} = 1.05 \pm 0.05 \text{ pb})$$

N.Kidonakis, Phys.Rev.D 81, 054028

- ✓ Accepted to publish this combination result by PRL with s-channel cross section measurement in  $E_T^{\text{miss}} b\bar{b}$  events at May 1, 2014 (arXiv:1402.3756)



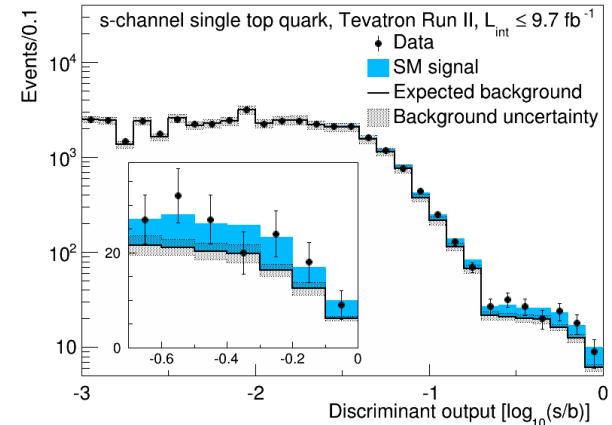
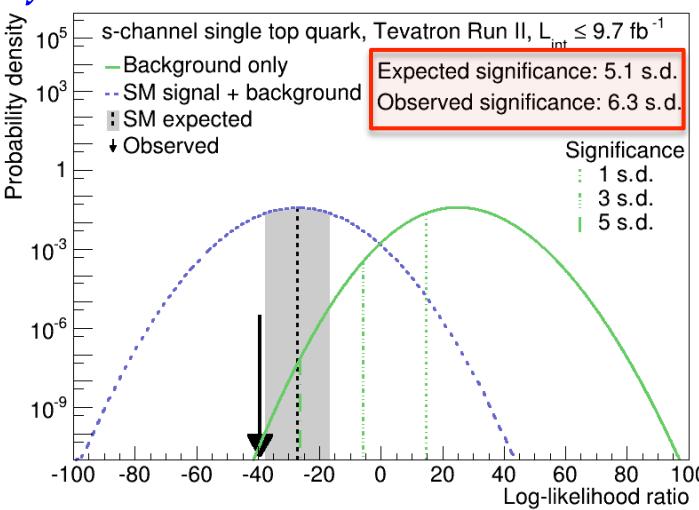
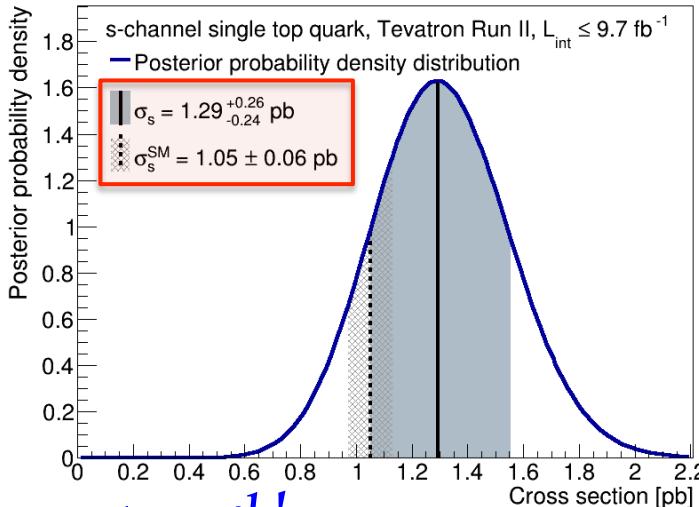
# Tevatron s-channel combination



New

Accepted to  
publish in PRL  
at Apr. 24, 2014  
(arXiv:1402.5126)

*First observation of s-channel!*



s-channel single top quark, Tevatron Run II,  $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$

Measurement

Cross section [pb]

CDF  $l+jets$

$1.41^{+0.44}_{-0.42}$

CDF  $E_T+jets$

$1.12^{+0.61}_{-0.57}$

CDF combined

$1.36^{+0.37}_{-0.32}$

D0  $l+jets$

$1.10^{+0.33}_{-0.31}$

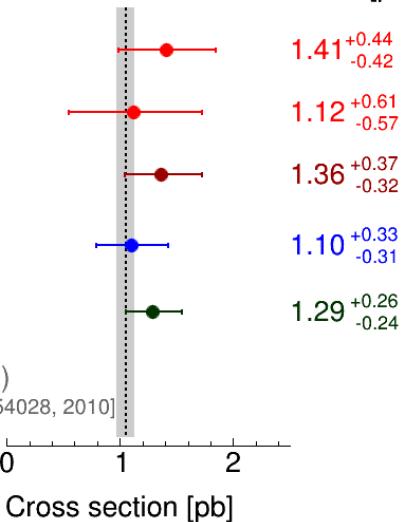
Tevatron combined

$1.29^{+0.26}_{-0.24}$

Theory (NLO+NNLL)

$1.05 \pm 0.06 \text{ pb}$  [PRD 81, 054028, 2010]

$m_{\text{top}} = 172.5 \text{ GeV}$



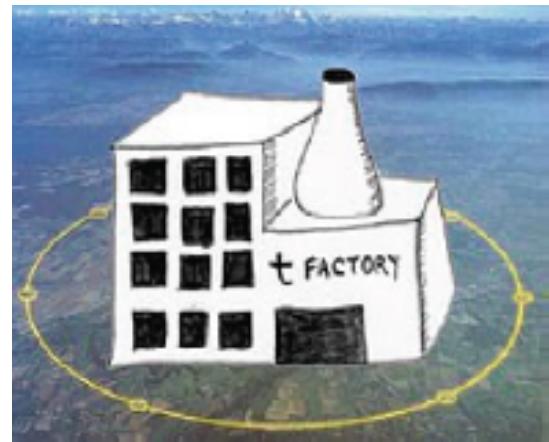
# Single top at the LHC

- ✓  $pp$  collision at  $\sqrt{s} = 7$  and 8 TeV
- ✓ CMS and ATLAS experiments
- ✓ Run I (2010–12) :  $\sim 5 \text{ fb}^{-1}$  (7 TeV),  $\sim 20 \text{ fb}^{-1}$  (8 TeV)
- ✓ The  $t$  and  $tW$  channel processes are dominant.  $s$ -channel not reachable yet.

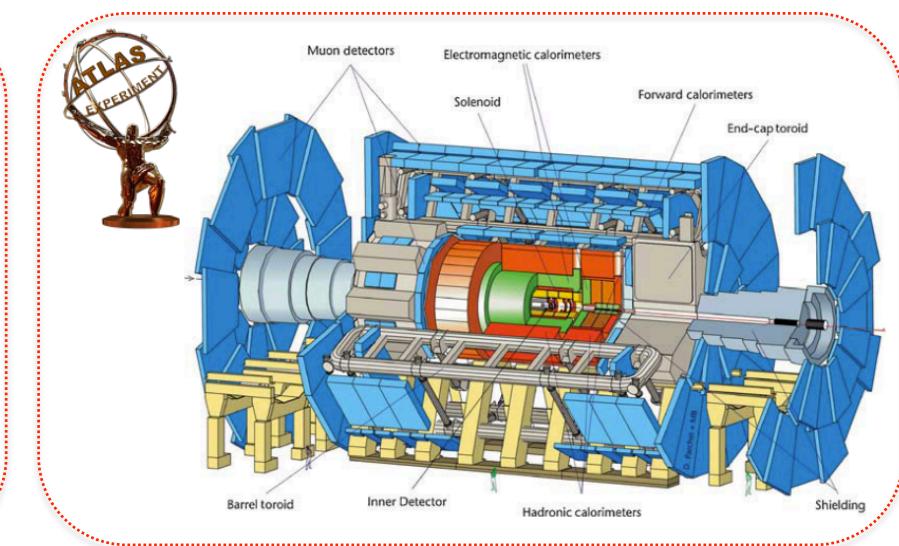
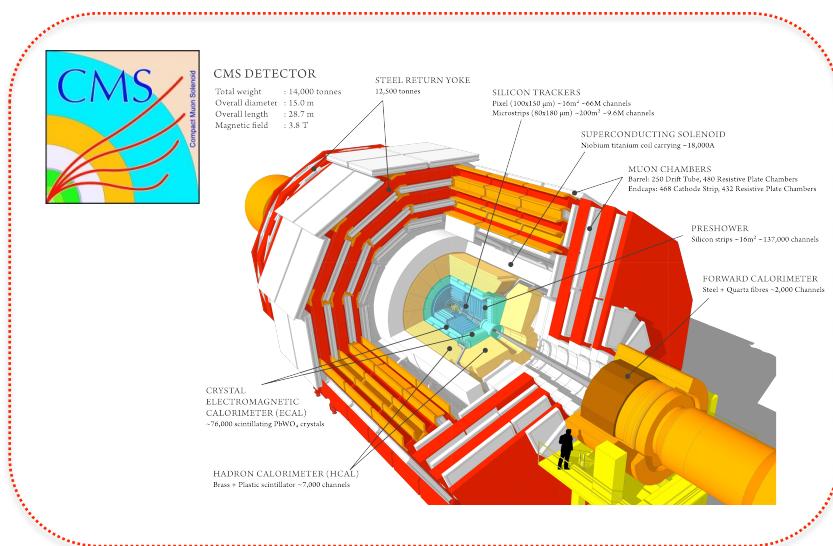
LHC 7 TeV	$\sigma(t) + \sigma(\bar{t})$ (pb)
$t$ -channel	$65.9^{+2.1+1.5}_{-0.7-1.7}$
$s$ -channel	$4.56 \pm 0.07^{+0.18}_{-0.17}$
$tW$	$15.6 \pm 0.4 \pm 1.1$

LHC 8 TeV	$\sigma(t) + \sigma(\bar{t})$ (pb)
$t$ -channel	$87.2^{+2.8+2.0}_{-1.0-2.2}$
$s$ -channel	$5.55 \pm 0.08 \pm 0.21$
$tW$	$22.2 \pm 0.6 \pm 1.4$

$m_{\text{top}} = 173 \text{ GeV}$ , Kidonakis, arXiv:1210.7813 (2012)



*LHC : top quark factory!*





# t-channel measurement at ATLAS

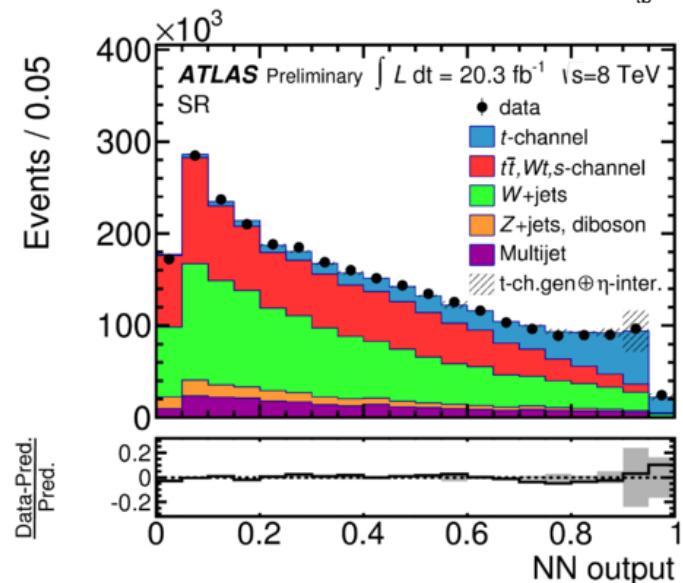
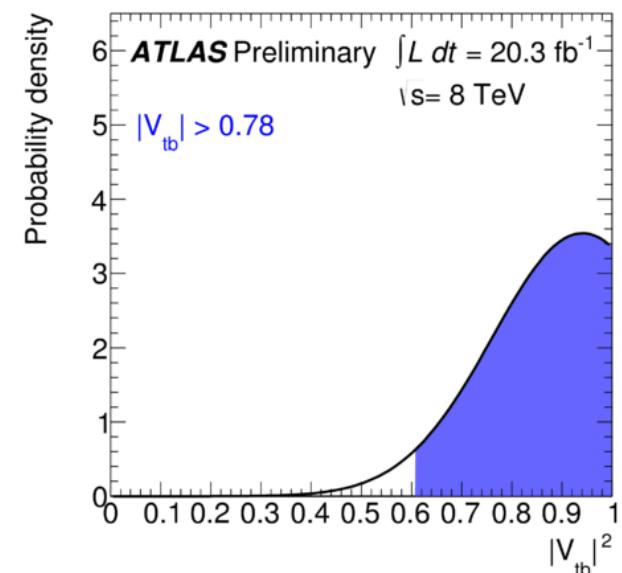
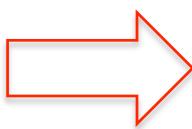
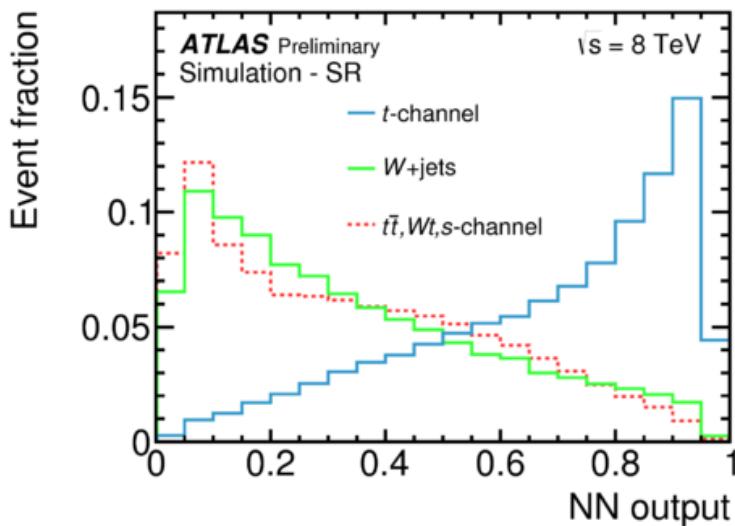
## ✓ Event Selection

- 1 isolated electron or muon ( $p_T > 25 \text{ GeV}/c$ )
- 2 jets (at least one b-tagging,  $E_T > 30 \text{ GeV}/c^2$ )
- MET  $> 30 \text{ GeV}/c^2$ , Transverse W-boson mass,  $m_T(W) > 50 \text{ GeV}$
- $\Delta R$  (lepton, jet)  $> 0.4$



## ✓ Result

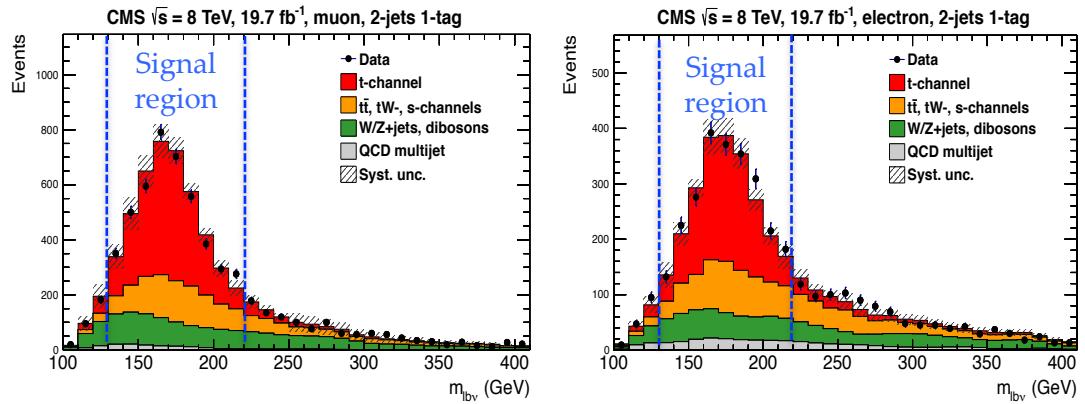
- $\sigma_t = 82.6 \pm 1.2 \text{ (stat.)} \pm 11.4 \text{ (syst.)} \pm 3.1 \text{ (PDF)} \pm 2.3 \text{ (lumi.) pb}$ 
  - SM prediction :  $87.2^{+2.8+2.0}_{-1.0-2.2} \text{ pb}$
- $|V_{tb}| = 0.97^{+0.09}_{-0.10} \text{ } (|V_{tb}| > 0.78 \text{ at 95 \% C.L.})$



# t-channel measurement at CMS

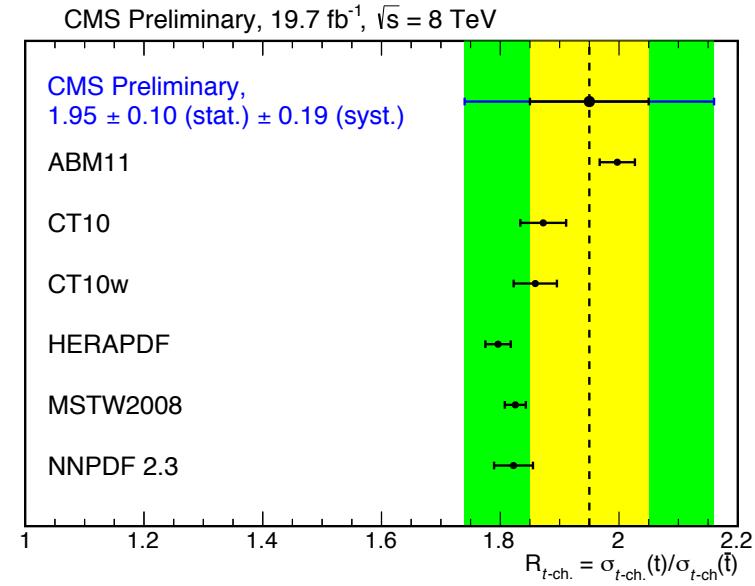
## ✓ Event Selection

- 1 isolated lepton
  - electron ( $p_T > 30 \text{ GeV}/c$ )
  - muon ( $p_T > 26 \text{ GeV}/c$ )
- 2 High  $E_T$  jets
  - At least one b-tagging,  $E_T > 40 \text{ GeV}/c^2$
- Kinematic cuts (anti QCD):
  - $m_T(W) > 50 \text{ GeV}$  for muon
  - MET  $> 45 \text{ GeV}/c^2$  for electron
- Signal region :  $130 < m_{lbv} < 220 \text{ GeV}$



## ✓ Result

- $\sigma = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.}) \text{ pb}$  (SM:  $87.2^{+2.8+2.0}_{-1.0-2.2}$ )
- $|V_{tb}| = 0.98 \pm 0.05(\text{exp.}) \pm 0.02(\text{th.})$ 
  - $|V_{tb}| > 0.92 \text{ (95\% C.L.)}$
- Accepted to publish in JHEP
- Charge ratio
  - $\sigma_{\text{top}} = 53.8 \pm 1.5(\text{stat.}) \pm 4.4(\text{syst.}) \text{ pb}$ 
    - SM :  $\sigma_{\text{top}} = 56.4 (+2.1-0.3) \pm 1.1 \text{ pb}$
  - $\sigma_{\text{anti-top}} = 27.6 \pm 1.3(\text{stat.}) \pm 4.4(\text{syst.}) \text{ pb}$ 
    - SM :  $\sigma_{\text{anti-top}} = 30.7 \pm 0.7 (+0.9-1.1) \text{ pb}$
  - $R(\text{top/anti-top}) = 1.95 \pm 0.10(\text{stat.}) \pm 0.19(\text{syst.})$





# First evidence of $tW$ -channel at ATLAS

## ✓ Event Selection

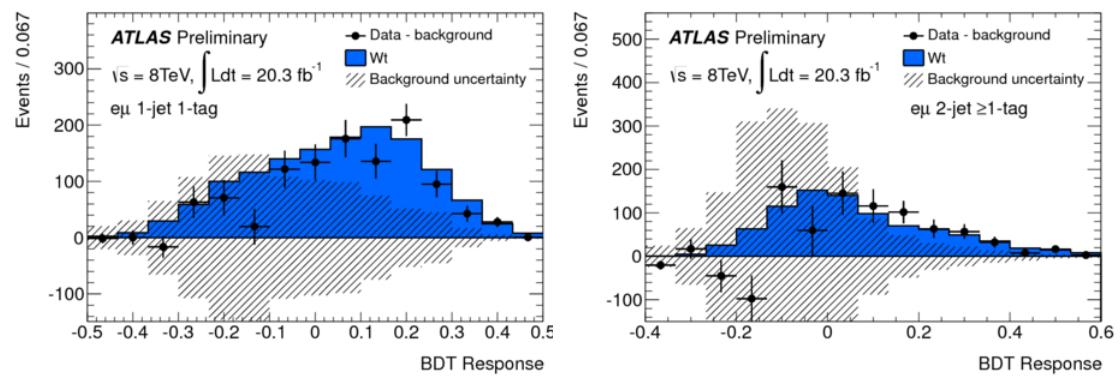
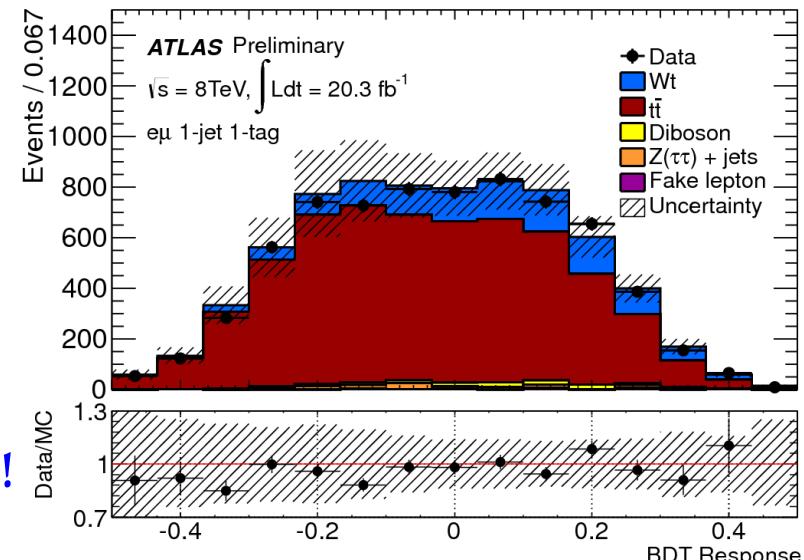
- 2 High  $p_T$  opposite-charge isolated leptons (ee,  $\mu\mu$  and  $e\mu$ )
  - Electron, Muon  $p_T > 25 \text{ GeV}/c$
- 1 or 2 jets (at least one b-tagging,  $E_T > 30 \text{ GeV}/c^2$ )
- BDT classifier discriminates the signal from background
  - 19 variables (1 jet), 20 variables (2 jet)

## ✓ Result

- $\sigma_{tW} = 27.2 \pm 2.8(\text{stat}) \pm 5.4(\text{syst}) \text{ pb}$ 
  - SM prediction:  $22.2 \pm 0.6 \pm 1.4 \text{ pb}$
- Significance:  **$4.2\sigma$  ( $4.0\sigma$  expected)**
- $|V_{tb}| = 1.10 \pm 0.12(\text{exp}) \pm 0.03(\text{th})$ 
  - $|V_{tb}| > 0.72$  at 95%CL

First evidence of  $tW$ -channel!

Process	1-jet	2-jet
$Wt$	$1140 \pm 190$	$710 \pm 100$
$t\bar{t}$	$5700 \pm 800$	$12700 \pm 1400$
Diboson	$120 \pm 30$	$79 \pm 28$
$Z(\tau\tau) + \text{jets}$	$110 \pm 40$	$90 \pm 40$
Fake lepton	$27 \pm 14$	$22 \pm 11$
Total Expected	$7100 \pm 1100$	$13600 \pm 1600$
Data Observed	6906	13159



# First observation of $tW$ -channel at CMS

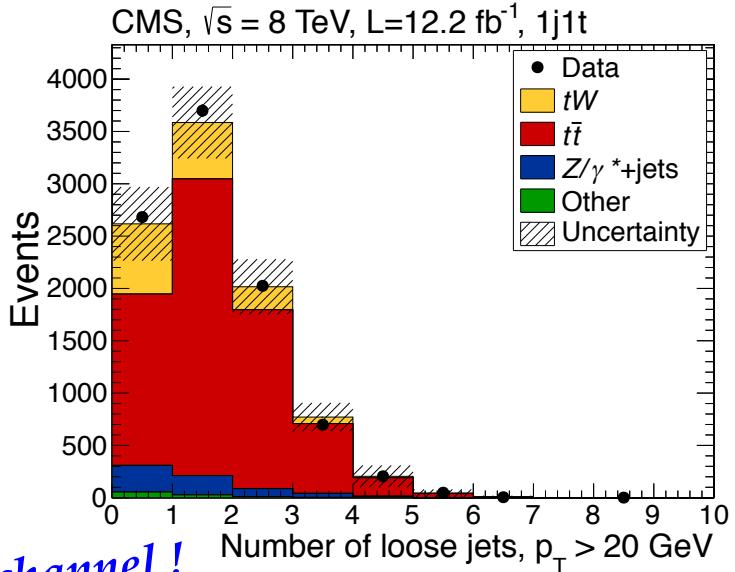
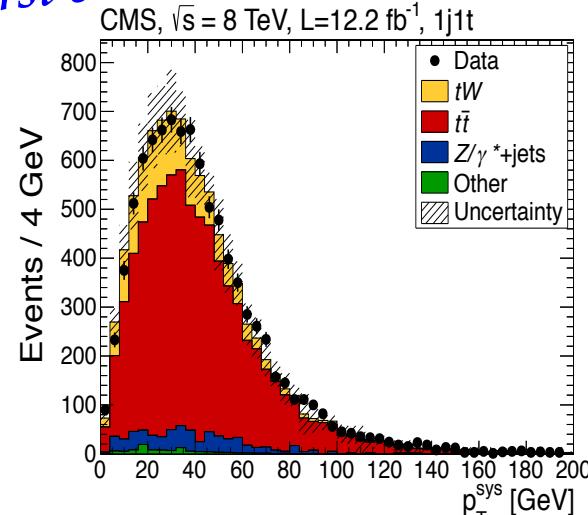
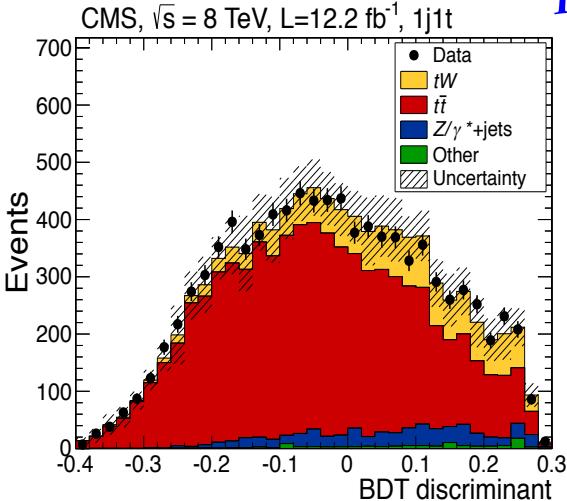
## ✓ Event Selection

- 2 isolated leptons, opposite charge ( $e, \mu$ )
- Only 1 jet, b-tagging required (**1j1t**)
- MET  $> 30$  GeV/c $^2$
- Veto of Z mass window ( $m_{ll}$ )
- BDT build with 13 variables (variables related to loose jets most powerful to discriminate)

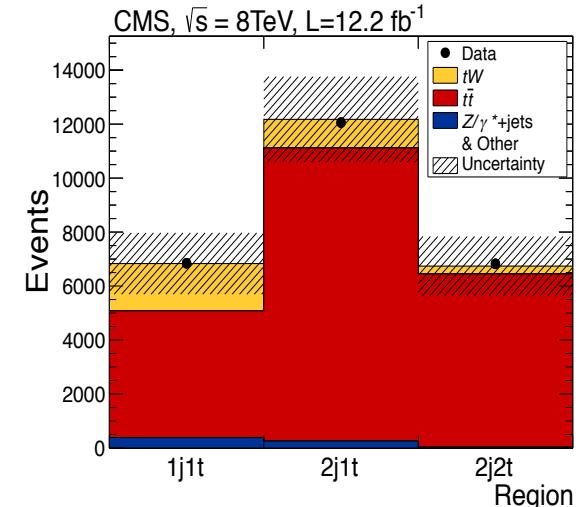


## ✓ Result

- $\sigma_{tW} = 23.4 \pm 5.4$  pb (SM :  $22.2 \pm 0.6 \pm 1.4$  pb)
- $tW$  signal observed with a significance of  **$6.1\sigma$  (5.4 expected)**
- $|V_{tb}| = 1.03 \pm 0.12$  (exp.)  $\pm 0.04$  (th.)  $\rightarrow |V_{tb}| > 0.78$  (95% C.L.)
- Accepted by PRL (arXiv:1401.2942)



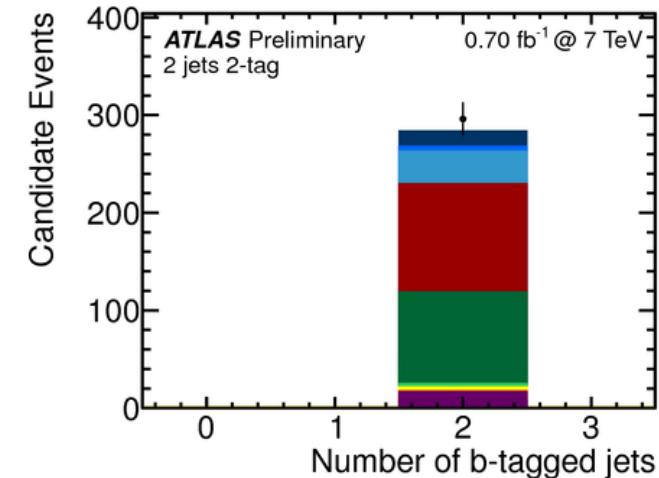
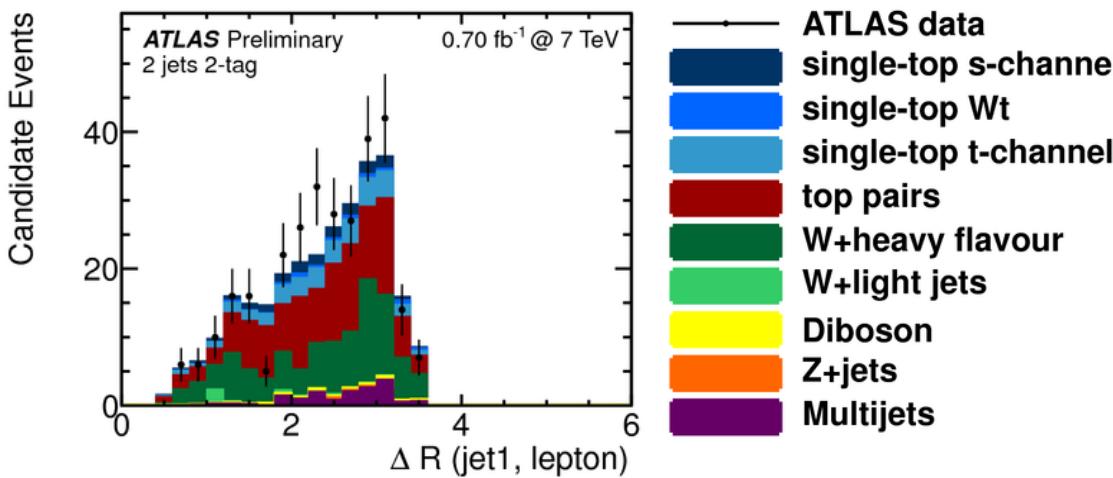
*First observation of  $tW$ -channel !*



# Search for s-channel at ATLAS

- ✓ First search s-channel single top at 7 TeV
- ✓ Event Selection
  - 1 high  $p_T$  electron or muon ( $P_T > 25 \text{ GeV}/c$ )
  - MET  $> 25 \text{ GeV}/c^2$
  - $m_T(W) > 60 \text{ GeV} - \text{MET}$
  - 2 jets ( $p_T > 25 \text{ GeV}/c$ , at least 1 b-tagging)
  - NN discriminate : 15 variables 2j1t, 19 variables 3j1t
  - training done in 4 channels (2 regions,  $l^+$  or  $l^-$ )
- ✓ Results
  - $\sigma_{\text{s-channel}} < 26.5 \text{ pb}$  at 95%CL (< 20.5 pb expected)
  - This corresponds to about 5 times the signal SM cross-section ( $4.56 \pm 0.07^{+0.18}_{-0.17} \text{ pb}$ )

Final Selection	
<i>s</i> -channel	$16 \pm 6$
<i>t</i> -channel	$33 \pm 13$
<i>Wt</i>	$5 \pm 3$
$t\bar{t}$	$111 \pm 47$
<i>W+jets</i>	$4 \pm 5$
<i>Wc+jets</i>	$10 \pm 8$
<i>Wc\bar{c}+jets</i>	$14 \pm 12$
<i>Wb\bar{b}+jets</i>	$70 \pm 51$
<i>Z+jets</i>	$1 \pm 1$
Diboson	$4 \pm 1$
Multijets	$17 \pm 10$
TOTAL Exp	$285 \pm 17$
$S/\sqrt{B}$	0.98
DATA	296



# Search for s-channel at CMS

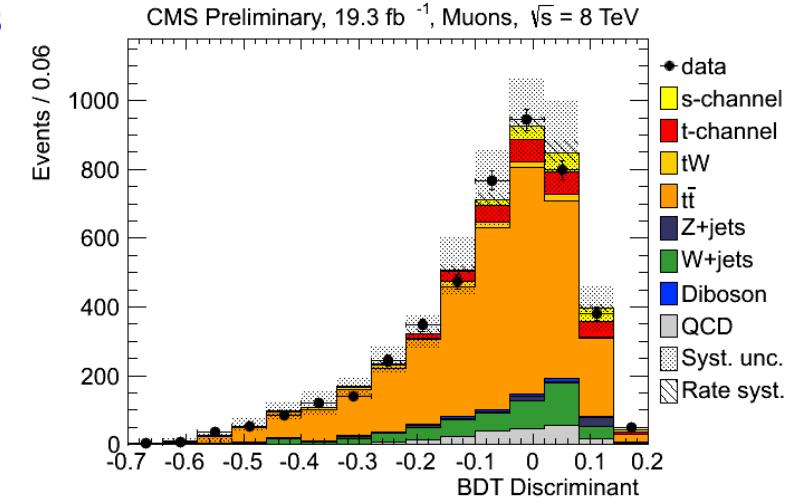
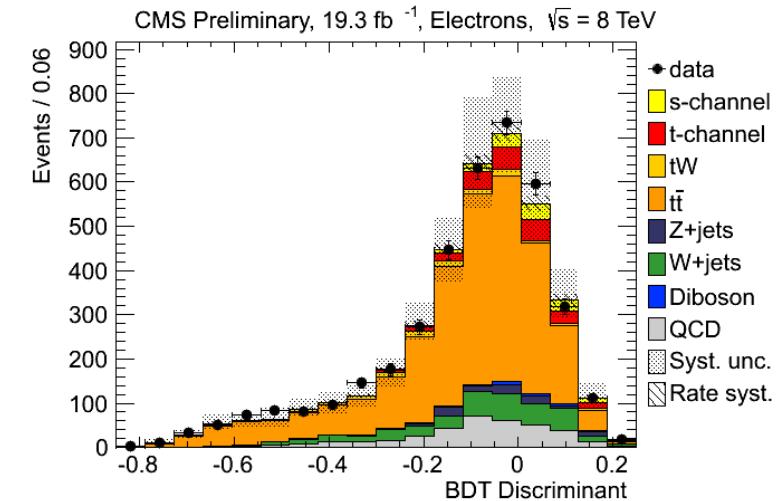
## ✓ Event Selection

- 1 isolated electron or muon ( $P_T > 30 \text{ GeV}/c$ )
- Missing Transverse Energy
- 2 b-tagged jets ( $E_T = 40/30 \text{ GeV}/c^2$ )
- Multivariate analysis based on a BDT :
  - 11 variables for electron, 10 for muon

## ✓ Result

- $\sigma_{s\text{-ch.}} = 5.9^{+8.6}_{-5.1} \text{ pb}$  muon channel
- $\sigma_{s\text{-ch.}} = 6.9^{+8.7}_{-5.7} \text{ pb}$  electron channel
- $\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1} \text{ pb}$  combined
- SM prediction:  $5.55 \pm 0.08 \pm 0.21 \text{ pb}$
- s-channel signal observed significance  **$0.7\sigma$  ( $0.9\sigma$  expected)**
- **Upper limit on the cross section times branching ratio of  $11.5 \text{ pb}$  at  $95\%$  C.L.**

Process	$\mu$ 3-jets 2-tags	$\mu$ 2-jets 2-tags	$e$ 3-jets 2-tags	$e$ 2-jets 2-tags
$t\bar{t}$	$10043 \pm 604$	$3144 \pm 189$	$8010 \pm 494$	$2483 \pm 154$
$W + jets$	$446 \pm 92$	$449 \pm 93$	$370 \pm 76$	$361 \pm 77$
$Z + jets$	$112 \pm 32$	$65 \pm 20$	$97 \pm 29$	$89 \pm 27$
Diboson	$36 \pm 8$	$45 \pm 10$	$33 \pm 7$	$37 \pm 8$
QCD	$353 \pm 74$	$209 \pm 52$	$222 \pm 19$	$363 \pm 69$
$tW$ -channel	$336 \pm 28$	$102 \pm 11$	$259 \pm 22$	$105 \pm 11$
$t$ -channel	$949 \pm 61$	$271 \pm 18$	$750 \pm 49$	$217 \pm 15$
s-channel	$87 \pm 5$	$168 \pm 10$	$70 \pm 4$	$131 \pm 8$
Total MC	$12361 \pm 750$	$4455 \pm 286$	$9811 \pm 606$	$3786 \pm 253$
Data	11979	4450	10149	3884



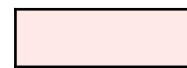
# Summary

- ✓ Presented the most latest single top results at the Tevatron and LHC.

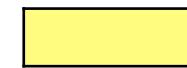
$\sigma$ [pb]		t-channel	tW	s-channel
Tevatron (1.96 TeV)	CDF	$1.49^{+0.47}_{-0.42}$ pb	-	1.046
	DØ	$3.07^{+0.53}_{-0.49}$ pb	-	$1.10^{+0.33}_{-0.31}$ pb
LHC (8 TeV)	CMS	$83.6 \pm 7.7$ pb	$23.4 \pm 5.4$ pb	< 11.5 pb
	ATLAS	$82.6 \pm 11.9$ pb	$27.2 \pm 6.1$ pb	< 26.5 pb



: Observed or Evidence



: Not yet observed



: Not accessible

- ✓ All single top production processes are observed with the recent observations from the Tevatron and LHC.
  - Observation of s-channel production from the Tevatron.
  - Observation of tW associated production from CMS.
  - The all measurements are agreed well with the Standard Model.
- ✓ More precise measurements for top quark properties will be performed with the single top events at LHC.